

AIR CYLINDER CONTROLLER

This application claims the benefit of U.S. Provisional Application Serial No. 60/444,074, filed January 31, 2003.

Background

The present invention particularly relates to controlled operation of dampers in heating and air conditioning systems, especially high volume air conditioning (HVAC) systems, 5 and will be described with particular reference thereto. The invention relates more generally to controlled operation of air cylinders and pneumatic/mechanical transducer systems, particularly for controlling fluid flow.

10 In heating and air conditioning systems, conditioned air is distributed through a house, office building, or other structure through air ducts. Typically, the conditioned air is forced through a duct at a constant air speed, and control of the heating or cooling for a particular room or area of the house, office building, or other structure is effected by 15 partially restricting air flow through a duct using one or more strategically placed dampers.

The damper setting is typically effected through a pneumatic actuating system that includes an electropneumatic transducer, such as an air cylinder controlled by an electronic 20 air pressure regulator, which operates on the damper. The air pressure regulator pressurizes or exhausts the air cylinder to cause an actuating arm of the air cylinder to move, thus causing the damper setting to be adjusted.

A problem arises in that air cylinders and other 25 pneumatic devices can exhibit hysteresis, pressure drift, frictional settling delays, and other operating non-linearities

and non-regularities. These non-regularities are usually air cylinder-specific, and may be different even for nominally similar air cylinders of the same make and model. Moreover, the operating non-regularities depend upon the operating environment 5 of the air cylinder or other pneumatic device. Thus, the air cylinder characteristics may depend upon the type of damper being controlled, the air flow through the duct, and similar parameters.

Control of such pneumatic devices is difficult, 10 because the hysteretic, frictional, mechanical or other delays result in long settling times as the air cylinder relaxes to a steady state. During this settling time, the pressure transiently varies in the air cylinder. The air pressure regulator attempts to respond to such transient pressure 15 variations by repeatedly switching between pressurizing and exhausting the air cylinder. This can further increase the settling time, and additionally creates noises that travel through the ducts of the HVAC system and can be disturbing to people in the house, office building, or other structure.

20 The present invention contemplates an improved apparatus and method that overcomes the aforementioned limitations and others.

Brief Summary

According to one aspect, an air flow regulator is 25 disclosed. A pneumatic cylinder is operatively connected with a damper to adjust a damper setting. A pressure sensor indicates a pneumatic pressure in the pneumatic cylinder. An air pressure regulator is operatively connected with the pneumatic cylinder to pressurize or exhaust the pneumatic cylinder responsive to an 30 electrical input indicative of a selected steady state pressure. The air pressure regulator includes a calibration table associating steady state pneumatic cylinder pressure values with regulator shut-off pressure values. The calibration table is addressed by the electrical input indicative of an updated

steady-state pneumatic cylinder pressure value. The calibration table retrieves a shutoff pressure value corresponding to the electrical input. The air pressure regulator ceases the pressurizing or exhausting at the retrieved shutoff pressure 5 value such that the steady state pressure in the pneumatic cylinder settles at about the selected steady state pressure.

According to another aspect, a method is provided for controlling a pneumatic cylinder which has a lag between termination of pressurization or evacuation and reading a steady 10 state pressure. A desired steady-state pressure is received. A shut-off pressure corresponding to the desired steady-state pressure is retrieved. The shut-off pressure is different from the corresponding steady state pressure. The pneumatic cylinder is pressurized or exhausted. The pressurizing or exhausting is 15 terminated when a measured pneumatic cylinder pressure corresponds to the shut-off pressure.

According to another aspect, a storage medium encodes instructions executed by a computer or microprocessor to perform a control method for controlling an electropneumatic transducer. 20 The control method includes: constructing a table associating steady state pressures with pressure regulator shutoff pressures; receiving a steady-state pressure value; retrieving a shutoff pressure corresponding to the steady state pressure from the table; and causing a pressure regulator to operate open 25 loop on the electropneumatic transducer until a pressure feedback signal associated with the electropneumatic transducer reaches the retrieved shutoff pressure. Upon the pressure feedback signal reaching the shutoff pressure, the control method causes the pressure regulator to cease operating on the 30 electropneumatic transducer.

According to yet another aspect, a controller is disclosed for controlling an electropneumatic transducer. An air pressure regulator has a first valve for selectively connecting and disconnecting a pressurized air supply and a second valve 35 for selectively connecting and disconnecting an exhaust.

Configurable electronics are configured to receive a steady state pressure, access a configured calibration to obtain a shut-off pressure associated with the received steady state pressure, cause a selected one of the first valve and the second 5 valve to connect, and cause the selected one of the first valve and the second valve to disconnect responsive to an instantaneous pressure corresponding to the obtained shut-off pressure.

According to still yet another aspect, a method of 10 regulating air flow in a duct system with a pneumatic cylinder controlled damper is provided. An air flow is selected. The selected air flow is converted into a corresponding steady state pneumatic cylinder pressure. A corresponding shutoff pressure is determined from which the pneumatic cylinder will settle at the 15 corresponding steady state pressure. Pressure in the pneumatic cylinder is changed until the shutoff pressure is reached. The pneumatic cylinder is allowed to settle from the shutoff pressure to the steady state pressure corresponding to the selected flow rate.

20 One advantage resides in reduced noise during damper operation.

Another advantage resides in more rapid transient response and reduced settling time for damper setting changes.

Yet another advantage resides in ready adaptation of 25 the pneumatic control for specific characteristics of the damper, air cylinder, draft characteristics, and other parameters of the air conditioning system.

Numerous additional advantages and benefits of the present invention will become apparent to those of ordinary 30 skill in the art upon reading the following detailed description of the preferred embodiments.

Brief Description of the Drawings

The invention may take form in various components and arrangements of components, and in various process operations

and arrangements of process operations. The drawings are only for the purpose of illustrating preferred embodiments and are not to be construed as limiting the invention.

5 FIGURE 1 diagrammatically shows a portion of a high volume air conditioning (HVAC) system including a controlled damper.

FIGURE 2 shows a flow chart of a preferred method for controlling the damper of FIGURE 1.

10 FIGURE 3A shows a preferred method for constructing a pressurizing portion of the calibration table of FIGURE 1.

FIGURE 3B shows a preferred method for constructing an exhausting portion of the calibration table of FIGURE 1.

15 FIGURE 3C shows a preferred method for automatically updating the calibration table of FIGURE 1 each time a new damper setting is applied.

Detailed Description of the Preferred Embodiments

With reference to FIGURE 1, a high volume air conditioning (HVAC) system 10 includes a plurality of ducts that convey heated, cooled or otherwise conditioned air throughout a 20 building or other structure. In FIGURE 1, the duct system is represented by exemplary duct 12. At selected places throughout the duct system, dampers are arranged to selectively control air flow. In FIGURE 1, the various dampers are represented by an exemplary damper 14, which is a hinged damper. However, 25 butterfly dampers, louvered dampers, or the like, and various combinations of such dampers, can also be employed. The HVAC system 10 typically further includes selected other components known in the art, such as a furnaces, flues, air conditioning units, particulate filters, registers, return air ducts, and the 30 like, which are not shown in FIGURE 1.

The damper 14 is moved by a pneumatic actuator, which in the exemplary embodiment of FIGURE 1 is an air cylinder 20. The pneumatic air cylinder 20 includes a generally cylindrical body 22 that contains a biased piston 24 that is biased by a

compressed spring **26** toward a compressed air volume **28**. In operation, an air line **30** delivers compressed air to pressurize the compressed air volume **28**. The increased pressure drives the piston **24** against the bias spring **26**. To move the piston **24** in the reverse direction, the air line **30** partially or totally exhausts the compressed air volume **28** to reduce the pressure in the compressed air volume **28**. In response to the reduced pressure, the bias spring **26** moves the piston **24** toward the compressed air volume **28**. An actuator arm **32** attached to the piston **24** communicates the linear piston motion of the piston **24** to the damper **14**, where intervening gearing or other mechanical components (not shown) convert linear motion of the actuator arm **32** into movement of the damper **14**.

The damper **14** is controlled via the air cylinder **20** by a controller **40**, which includes an air pressure regulator **42**. The air pressure regulator **42** includes a first valve **44** that selectively connects the air line **30** with a pressurized air supply **46**. The air pressure regulator also includes a second valve **48** that selectively connects the air line **30** with an exhaust pathway **50**, which in a preferred embodiment exhausts to the ambient air. Alternatively, the pressurized air supply **46** can be replaced by another gas or a liquid (in the latter case providing hydraulic operation), in which case the exhaust pathway **50** is preferably contained. A pressure sensor **52** provides a pressure feedback signal indicative of instantaneous pressure in the air line **30**. As the air line **30** is in continuous fluid communication with the pressurized air volume **28** of the air cylinder **20**, the pressure sensor **52** monitors pressure in the air volume **28** of the air cylinder **20**. Of course, a pressure sensor physically located at and directly monitoring the pressurized air volume **28** can also be employed.

The controller **40** further includes a processor **60** that selectively operates the valves **44**, **48** to place the air pressure regulator **42** into one of three states: a pressurizing state in which the first valve **44** is open to connect the

pressurized air supply **46** with the compressed air volume **28** of the air cylinder **20** and the second valve **48** is closed; an exhaust state in which the first valve **44** is closed and the second valve **48** is open to connect the compressed air volume **28** with the exhaust pathway **50**; and an isolation state in which both valves **44**, **48** are closed to pneumatically isolate the compressed air volume **28** of the air cylinder **20**.

The processor **60** is suitably a microcontroller, a microprocessor, a computer, or the like, which executes software instructions stored on a non-volatile medium **62** which is suitably embodied as an electronic read-only memory, a Flash memory, a magnetic disk, an optical disk, or the like. In a preferred embodiment the non-volatile storage medium **62** is a programmable read-only memory (PROM), erasable PROM (EPROM), Flash memory, or the like integrated with the processor **60** or connected with the processor **60** by printed circuitry of a printed circuit board. The controller **40** further includes a calibration table **64** which provides a correlation between instantaneous pressures at which the air pressure regulator **42** is placed in the isolation state and corresponding steady state pressures in the compressed air volume **28** of the air cylinder **20**. The calibration table **64** can be stored in a Flash memory, magnetic storage medium, or other read/write-capable non-volatile memory. The processor **60** receives a steady state pressure **70** from the HVAC system controller (not shown) and operates the valves **44**, **48** to set the air cylinder **20** to that steady state pressure.

With continuing reference to FIGURE 1 and with further reference to FIGURE 2, in a preferred embodiment the non-volatile storage medium **62** stores a software program that instructs the processor **60** to cause the controller **40** to perform a control method **100** in response to receiving a new steady state pressure **70**. By comparing the new steady state pressure **70** with the present reading of the pressure sensor **52**, a selection is made **102** as to whether the air pressure controller **42** should act

to further pressurize the air volume **28** or to partially or fully exhaust the air volume **28** in order to attain the target steady state pressure **70**.

As is known in the art, certain pneumatic actuators such as the air cylinder **20** typically exhibit hysteresis, pressure drift, frictional settling delays, and other operating non-linearities and non-regularities. Feedback control of such pneumatic devices typically exhibits long settling times, erratic convergence to steady state, and noisy operation due to repeated pressurizing and exhausting responsive to the non-regularities which are difficult to model and account for within a PID or other conventional control framework.

To overcome these difficulties, the method **100** employs an open loop control based on parameters stored in the calibration table **64**. In a preferred embodiment which recognizes that the operating non-regularities are generally different for the pressurization and exhausting operations of the air cylinder **20**, the calibration table **64** includes a pressurizing calibration table **64P** and an exhausting calibration table **64E**. The calibration values store shutoff pressure values that correspond to steady state pressure values.

Thus, for the target steady state pressure value **70** and the selected direction of operation (pressurize or exhaust), a look-up **104** is performed in the appropriate calibration table **64E** (for exhausting) or **64P** (for pressurizing) to obtain a shutoff pressure corresponding to the target steady state pressure **70**. The lookup **104** preferably performs an interpolation between data points of the table **64** to obtain an appropriate shutoff pressure if the target steady state pressure **70** is not one of the data points of the calibration table **64**. Alternatively, the calibration table **64** can be in the form of empirical fitted mathematical expressions for the pressurizing and exhausting correspondence curves.

A branch **110** of the control method **100** selects the appropriate operation mode of the air pressure regulator **42**:

either pressurizing operation or exhausting operation. If pressurizing operation is selected, then in a process operation 112 the pressurized air supply 46 is connected with the air cylinder 20. This is suitably accomplished by placing the air 5 pressure regulator 42 into the pressurizing state in which the first valve 44 is open to connect the pressurized air supply 46 with the compressed air volume 28 of the air cylinder 20 and the second valve 48 is closed.

Alternatively, if exhausting operation is selected, 10 then in a process operation 114 the air cylinder 20 is connected with the exhaust pathway 50. This is suitably accomplished by placing the air pressure regulator 42 into the exhaust state in which the first valve 44 is closed and the second valve 48 is open to connect the compressed air volume 28 with the exhaust 15 pathway 50.

Once the appropriate operating state of the air pressure regulator 42 is established, the air cylinder 20 is pressurized or exhausted, causing an increase or reduction in pressure, respectively, over time. At a process operation 120, 20 the method 100 monitors the instantaneous pressure indicated by the pressure sensor 52 until the instantaneous pressure reaches the shutoff pressure obtained in the lookup operation 104.

When the shutoff pressure from the table 64P, 64E is reached, the pressurized air supply 46 or the exhaust pathway 50 25 is disconnected from the air cylinder 20 in a process operation 122. This is suitably accomplished by placing the air pressure regulator 42 into the isolation state in which both valves 44, 48 are closed to pneumatically isolate the compressed air volume 28 of the air cylinder 20.

Once isolated, the air cylinder typically exhibits 30 the hysteresis, pressure drift, frictional settling delays, or other operating non-linearities or non-regularities of the particular air cylinder 20. Such hysteresis, pressure drift, frictional settling delays, or other operating non-linearities 35 or non-regularities are accounted for in constructing the

calibration table **64**, so that pneumatic isolation of the air cylinder **20** at the shutoff pressure selected in the lookup operation **104** results in the air cylinder **20** settling in at the target steady state pressure **70**.

5 The calibration table **64** is preferably constructed empirically. The various non-linearities and non-regularities of the air cylinder **20** vary from air cylinder to air cylinder. While such non-regularities are usually consistent for a given specific air cylinder, there are commonly substantial variations 10 in the non-regularities between different air cylinders, and even between commercial air cylinders of the same model which are made by the same manufacturer.

15 Moreover, the hysteresis, pressure drift, frictional settling delays, or other operating non-linearities or non-regularities are affected by the environment in which the air cylinder operates. In the exemplary HVAC system **10**, such environmental parameters include air flow in the duct **12**, characteristics of the damper **14**, and mechanical characteristics of the connection between the actuator arm **32** and the damper **14**. 20 Hence, construction of the calibration table **64** is preferably performed *in situ*, that is, with the air cylinder **20** installed in the HVAC system **10** and connected with the specific damper **14** which is to be actuated.

25 With continuing reference to FIGURE 1 and with further reference to FIGURE 3A, in a preferred method **140** the pressurizing calibration table **64P** is constructed as follows. The air cylinder **20** is initially set to a low pressure in process **142**. This is accomplished by opening the second valve **48** and closing the first valve **44** (or maintaining the first valve 30 **44** in the closed state) for a time period sufficient to exhaust the air cylinder **20** to a low pressure, or until a selected low pressure is reached, followed by pneumatically isolating the air cylinder **20** by closing the second valve **48** while maintaining the first valve **44** in the closed state.

A first shutoff pressure is selected 144. This selected shutoff pressure should be greater than the initial low pressure setting of the process operation 142. The pressurized air supply 46 is connected to the air cylinder 20 in process 5 operation 146 by opening the first valve 44 and maintaining the second valve 48 in the closed state. The pressure sensor 52 is monitored 150 to detect when the instantaneous pressure corresponds to the shutoff pressure, at which point the pressurized air supply 46 is disconnected 152 from the air 10 cylinder 20 by closing the first valve 44 while maintaining the second valve 48 in the closed state. With both valves 44, 48 closed, the air pressure regulator 42 is in the isolation state, and the air cylinder 20 is pneumatically isolated.

The method 140 then pauses 156 for a preselected 15 settling delay time to allow the air cylinder 20 to settle to a steady state pressure. After the preselected delay 156, the pressure sensor 52 is read to determine the steady state pressure corresponding to the shutoff pressure, and the pressurizing calibration table 64P is updated 160 to indicate 20 correspondence between the measured steady state pressure and the shutoff pressure. The process operations 144, 146, 150, 152, 156, 160 are repeated 162 for several increasing shutoff pressures to complete the pressurizing calibration table 64P.

With continuing reference to FIGURES 1 and with 25 further reference to FIGURE 3B, in a preferred method 170 the exhausting calibration table 64E is constructed as follows. The air cylinder 20 is initially set to a high pressure in process 172. This is accomplished by opening the first valve 44 and closing the second valve 48 (or maintaining the second valve 48 30 in the closed state) until a selected high pressure is reached, followed by placing the air pressure regulator 42 into the isolation state by closing the first valve 44 while maintaining the second valve 48 in the closed state.

A first shutoff pressure is selected 174. This 35 selected shutoff pressure should be lower than the initial high

pressure setting of the process operation 172. The exhaust pathway 50 is connected to the cylinder in process operation 176 by opening the second valve 48 and maintaining the first valve 44 in the closed state. The pressure sensor 52 is monitored 180 5 to detect when the instantaneous pressure corresponds to the shutoff pressure, at which point the exhaust pathway 50 is disconnected 182 from the air cylinder 20 by closing the second valve 48 while maintaining the first valve 44 in the closed state. With both valves 44, 48 closed, the air pressure 10 regulator 42 is in the isolation state, and the air cylinder 20 is pneumatically isolated.

The method 170 then pauses 186 for a preselected settling delay time to allow the air cylinder 20 to settle to a steady state pressure. After the preselected delay 186, the 15 pressure sensor 52 is read to determine the steady state pressure corresponding to the shutoff pressure, and the exhaust calibration table 64E is updated 190 to indicate correspondence between the measured steady state pressure and the shutoff pressure. The process operations 174, 176, 180, 182, 186, 190 20 are repeated 192 for several decreasing shutoff pressures to complete the pressurizing calibration table 64E.

In employing the described calibration table construction methods 140, 170 for pressurizing and exhausting, respectively, it is recognized that hysteresis may cause the 25 pressurizing characteristics of the air cylinder 20 to be substantially different from the exhausting characteristics. However, for certain air cylinders the air cylinder response may be even more state-dependent. For example, a transition from one-quarter of full pressure to half of full pressure may have a 30 different transient response compared with a transition from substantially fully exhausted to half of full pressure. The calibration table 64 optionally includes additional correspondence data to account for such state-dependent characteristics.

Moreover, the calibrations 140, 170 may need to be repeated occasionally. In one embodiment, it is contemplated to perform the calibration methods 140, 170 at the installation of the air cylinder 20, and also after major maintenance to the air cylinder 20, damper 14, or other related components. Recalibration is also preferably performed after replacement of the damper 14, or after a substantial change in a rate of air flow through the duct 12. Optionally, the calibration table 64 is updated more frequently using an automated update method, as described next.

With continuing reference to FIGURES 1 and 2, and with further reference to FIGURE 3C, a suitable method 200 for automatically updating the calibration table 64 each time a setting of the damper 14 is changed is described. The method 200 is preferably performed after the initial calibrations 140, 170 are performed to initialize the calibration table 64. In the method 200, each time a damper setting is changed in accordance with the method 100, the processor 60 waits 202 a preselected settling period after the air cylinder 20 is isolated 122 in order to allow the air cylinder 20 to reach a steady state. After the delay 202, the pressure sensor 52 is read to ascertain the steady state pressure, which is used to influence the initial calibration table values to gradually improve accuracy. The pressure is recorded 204 as corresponding to the shutoff pressure used in the method 100.

The invention has been described with reference to the preferred embodiments. Obviously, modifications and alterations will occur to others upon reading and understanding the preceding detailed description. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.